first produced, and, if circumstances are favourable, this is further oxidised to carbon dioxide.

II. "On the Mechanical Conditions of a Swarm of Meteorites, and on Theories of Cosmogony." By G. H. DARWIN, LL.D., F.R.S., Fellow of Trinity College and Plumian Professor in the University of Cambridge. Received July 12, 1888.

(Abstract.)

Mr. Lockyer writes in his interesting paper on Meteorites* as follows:—

"The brighter lines in spiral nebulæ, and in those in which a rotation has been set up, are in all probability due to streams of meteorites with irregular motions out of the main streams, in which the collisions would be almost *nil*. It has already been suggested by Professor G. Darwin ('Nature,' vol. 31, p. 25)—using the gaseous hypothesis—that in such nebulæ 'the great mass of the gas is non-luminous, the luminosity being an evidence of condensation along lines of low velocity according to a well-known hydrodynamical law. From this point of view the visible nebula may be regarded as a luminous diagram of its own stream-lines.'"

The whole of Mr. Lockyer's paper, and especially this passage in it, leads me to make a suggestion for the reconciliation of two apparently divergent theories of the origin of planetary systems.

The nebular hypothesis depends essentially on the idea that the primitive nebula is a rotating mass of fluid, which at successive epochs becomes unstable from excess of rotation, and sheds a ring from the equatorial region.

The researches of Roche† (apparently but little known in this country) have imparted to this theory a precision which was wanting in Laplace's original exposition, and have rendered the explanation of the origin of the planets more perfect.

But notwithstanding the high probability that some theory of the kind is true, the acceptance of the nebular hypothesis presents great difficulties.

Sir William Thomson long ago expressed to me his opinion that the most probable origin of the planets was through a gradual accretion of meteoric matter, and the researches of Mr. Lockyer afford actual evidence in favour of the abundancy of meteorites in space.

* 'Nature,' Nov. 17, 1887. The paper itself is in 'Roy. Soc. Proc.,' Nov. 15, 1887 (No. 259, p. 117).

† 'Montpellier, Acad. Sci. Mém.'

But the very essence of the nebular hypothesis is the conception of fluid pressure, since without it the idea of a figure of equilibrium becomes inapplicable. Now, at first sight, the meteoric condition of matter seems absolutely inconsistent with a fluid pressure exercised by one part of the system on another. We thus seem driven either to the absolute rejection of the nebular hypothesis, or to deny that the meteoric condition was the immediate antecedent of the sun and planets. M. Faye has taken the former course, and accepts as a necessary consequence the formulation of a succession of events quite different from that of the nebular hypothesis.* I cannot myself find that his theory is an improvement on that of Laplace, except in regard to the adoption of meteorites, for he has lost the conception of the figure of equilibrium of a rotating mass of fluid.

The object of this paper is to point out that by a certain interpretation of the meteoric theory we may obtain a reconciliation of these two orders of ideas, and may hold that the origin of stellar and planetary systems is meteoric, whilst retaining the conception of fluid pressure.

According to the kinetic theory of gases fluid pressure is the average result of the impacts of molecules. If we imagine the molecules magnified until of the size of meteorites, their impacts will still, on a coarser scale, give a quasi-fluid pressure. I suggest then that the fluid pressure essential to the nebular hypothesis is in fact the resultant of countless impacts of meteorites.

The problems of hydrodynamics could hardly be attacked with success, if we were forced to start from the beginning and to consider the cannonade of molecules. But when once satisfied that the kinetic theory will give us a gas, which, in a space containing some millions of molecules, obeys all the laws of an ideal non-molecular gas filling all space, we may put the molecules out of sight and treat the gas as a plenum.

In the same way the difficulty of tracing the impacts of meteorites in detail is insuperable, but if we can find that such impacts give rise to a quasi-fluid pressure on a large scale, we may be able to trace out many results by treating an ideal plenum. Laplace's hypothesis implies such a plenum, and it is here maintained that this plenum is merely the idealisation of the impacts of meteorites.

As a bare suggestion this view is worth but little, for its acceptance or rejection must turn entirely on numerical values, which can only be obtained by the consideration of some actual system. It is obvious that the solar system is the only one about which we have sufficient knowledge to afford a basis for discussion. The paper, of which this is an abstract, is accordingly devoted to a consideration of the

* 'Sur l'Origine du Monde,' Paris, Gauthier-Villars, 1884. 'Annuaire pour l'an 1885, Bureau des Longitudes,' p. 757.

mechanics of a swarm of meteorites, with special numerical application to the solar system.

When two meteoric stones meet with planetary velocity, the stress between them during impact must generally be such that the limits of true elasticity are exceeded, and it may be urged that a kinetic theory is inapplicable unless the colliding particles are highly elastic. It may, however, I think, be shown that the very greatness of the velocities will impart what virtually amounts to an elasticity of a high order of perfection.

It appears, *à priori*, probable that when two meteorites clash, a portion of the solid matter of each is volatilised, and Mr. Lockyer considers the spectroscopic evidence conclusive that it is so. There is no doubt enough energy liberated on impact to volatilise the whole of both bodies, but only a small portion of each stone will undergo this change. A numerical example is given in the paper to show the enormous amount of energy with which we are dealing. It must necessarily be obscure as to how a small mass of solid matter *can* take up a very large amount of energy in a small fraction of a second, but spectroscopic evidence seems to show that it does so; and if so, we have what is virtually a violent explosive introduced between the two stones.

In a direct collision each stone is probably shattered into fragments, like the splashes of lead when a bullet hits an iron target. But direct collision must be a comparatively rare event. In glancing collisions the velocity of neither body is wholly arrested, the concentration of energy is not so enormous (although probably still sufficient to effect volatilisation), and since the stones rub past one another, more time is allowed for the matter round the point of contact to take up the energy; thus the whole process of collision is much more intelligible. The nearest terrestrial analogy is when a cannon-ball rebounds from the sea. In glancing collisions fracture will probably not be very frequent.

From these arguments it is probable that, when two meteorites meet, they attain an effective elasticity of a high order of perfection; but there is of course some loss of energy at each collision.

[It must, however, be admitted that on collision the deflection of path is rarely a very large angle; but a succession of glancing collisions would be capable of reversing the path, and thus the kinetic theory of meteorites may be taken as not differing materially from that of gases.*]

Perhaps the most serious difficulty in the whole theory arises from the fractures which must often occur. If they happen with great frequency, it would seem as if the whole swarm of meteorites would degrade into dust. We know, however, that meteorites of consider-

* Added on November 16, 1888.

able size fall upon the earth, and, unless Mr. Lockyer has misinterpreted the spectroscopic evidence, the nebulæ do now consist of meteorites. Hence it would seem as if fracture was not of very frequent occurrence. It is easy to see that if two bodies meet with a given velocity the chance of fracture is much greater if they are large, and it is possible that the process of breaking up will go on only until a certain size, dependent on the velocity of agitation, is reached, and will then become comparatively unimportant.

When the volatilised gases cool they will condense into a metallic rain, and this may fuse with old meteorites whose surfaces are molten. A meteorite in that condition will certainly also pick up dust. Thus there are processes in action tending to counteract subdivision by fracture and volatilisation. The mean size of meteorites probably depends on the balance between these opposite tendencies. If this is so, there will be some fractures, and some fusions, but the mean mass will change very slowly with the mean kinetic energy of agitation. This view is at any rate adopted in the paper as a working hypothesis. It was not, however, possible to take account of fracture and fusion in the mathematical investigation, but the meteorites are treated as being of invariable mass.

The velocity with which the meteorites move is derived from their fall from a great distance towards a centre of aggregation. In other words, the potential energy of their mutual attraction when widely dispersed becomes converted, at least partially, into kinetic energy. When the condensation of a swarm is just beginning, the mass of the aggregation towards which the meteorites fall is small, and thus the new bodies arrive at the aggregation with small velocity. Hence initially the kinetic energy is small, and the volume of the sphere within which hydrostatic ideas are (if anywhere) applicable is also small. As more and more meteorites fall in, that volume is enlarged, and the velocity with which they reach the aggregation is increased. Finally the supply of meteorites in that part of space begins to fail, and the imperfect elasticity of the colliding bodies brings about a gradual contraction of the swarm. I do not now attempt to trace the whole history of a swarm, but the object of the paper is to examine its mechanical condition at an epoch when the supply of meteorites from outside has ceased, and when the velocities of agitation and distribution of meteorites in space have arranged themselves into a sub-permanent condition, only affected by secular changes. This examination will enable us to understand, at least roughly, the secular change as the swarm contracts, and will throw light on other questions.

The foundation for the mathematical investigation in the paper is the hypothesis that a number of meteorites which were ultimately to coalesce, so as to form the sun and planets, have fallen together from

a condition of wide dispersion, and form a swarm in which collisions are frequent.

For the sake of simplicity, the bodies are treated as spherical, and in the first instance as being of uniform size.

It is assumed provisionally that the kinetic theory of gases may be applied for the determination of the distribution of the meteorites in space. No account being taken of the rotation of the system, the meteorites will be arranged in concentric spherical layers of equal density of distribution, and the quasi-gas, whose molecules are meteorites, being compressible, the density will be greater towards the centre of the swarm. The elasticity of a gas depends on the kinetic energy of agitation of its molecules, and therefore in order to determine the law of density in the swarm we must know the distribution of kinetic energy of agitation.

It is assumed that when the system comes under our notice, uniformity of distribution of energy has been attained throughout a central sphere, which is surrounded by a layer of meteorites with that distribution of kinetic energy which, in a gas, corresponds to convective equilibrium, and with continuity of density and velocity of agitation at the sphere of separation. Since in a gas in convective equilibrium the law connecting pressure and density is that which holds when the gas is contained in a vessel impermeable to heat, such an arrangement of gas has been called by M. Ritter* an isothermal-adiabatic sphere, and the same term is adopted here as applicable to a swarm of meteorites. The justifiability of these assumptions will be considered later.

The first problem which presents itself then is the equilibrium of an isothermal sphere of gas under its own gravitation. The law of density is determined in the paper, but it will here suffice to remark that, if a given mass be enclosed in an envelope of given radius, there is a minimum temperature (or energy of agitation) at which isothermal equilibrium is possible. The minimum energy of agitation is found to be such that the mean square of velocity of the meteorites is almost exactly $\frac{6}{5}$ of the square of the velocity of a satellite grazing the surface of the sphere in a circular orbit.

As indicated above, it is supposed that in the meteor-swarm the rigid envelope, bounding the isothermal sphere, is replaced by a layer or atmosphere in convective equilibrium. The law of density in the adiabatic layer is determined in the paper, and it appears that when the isothermal sphere has minimum temperature, the mass of the adiabatic atmosphere is a minimum relatively to that of the isothermal sphere. Numerical calculation shows, in fact, that the isothermal sphere cannot amount in mass to more than 46 per cent. of the mass of the whole isothermal-adiabatic sphere, and that the limit of the

* 'Annalen der Physik und Chemie,' vol. 16 (1882), p. 166.

adiabatic atmosphere is at a distance equal to 2·786 times the radius of the isothermal sphere.*

It is also proved that the total energy, existing in the form of energy of agitation, is exactly one-half of the potential energy lost in the concentration of the matter from a condition of infinite dispersion. This result is brought about by a continual transfer of energy from a molar to a molecular form, for a portion of the kinetic energy of a meteorite is constantly being transferred into the form of thermal energy in the volatilised gases generated on collision. The thermal energy is then lost by radiation.

It is impossible as yet to sum up all the considerations which go to justify the assumption of the isothermal-adiabatic arrangement, but it is clear that uniformity of kinetic energy must be principally brought about by a process of diffusion. It is therefore interesting to consider what amount of inequality in the kinetic energy would have to be smoothed away.

The arrangement of density in the isothermal-adiabatic sphere being given, it is easy to compute what the kinetic energy would be at any part of the swarm, if each meteorite fell from infinity to the neighbourhood where we find it, and there retained all the velocity due to such fall. The variation of the square of this velocity gives an indication of the amount of kinetic energy which has to be degraded by conversion into heat and distributed by diffusion, in the attainment of uniformity. This may be called "the theoretical value of the kinetic energy." It appears that in the swarm, this square of velocity rises from zero at the centre of the swarm to a maximum, which is attained nearly half-way through the adiabatic layer, and then diminishes. It is found that the variations of this theoretical value are inconsiderable throughout the greater part of the range. Since this "theoretical value of the kinetic energy" is zero at the centre, there must be diffusion of kinetic energy from without inwards, and considerations of the same kind show that when a planet consolidates there must be a cooling of the middle strata both outwards and inwards.

We must now consider the nature of the criterion which determines whether the hydrostatic treatment of a meteor-swarm is permissible.

The hydrodynamical treatment of an ideal plenum of gas leads to the same result as the kinetic theory with regard to any phenomenon involving purely a mass, when that mass is a large multiple of the mass of a molecule; to any phenomenon involving purely a length, when the cube of that length contains a large number of molecules; and to any phenomenon involving purely a time, when that time is a large multiple of the mean interval between collisions. Again, any

* This is one of the results established by M. Ritter in a series of papers in the 'Annalen der Physik und Chemie' from 1878 onwards.

velocity to be justly deduced from hydrodynamical principles must be expressible as the edge of a cube containing many molecules passed over in a time containing many collisions of a single molecule; and a similar statement must hold of any other function of mass, length, and time.

Beyond these limits we must go back to the kinetic theory itself, and in using it care must be taken that enough molecules are considered at once to impart statistical constancy to their properties.

There are limits then to the hydrodynamical treatment of gases, and the like must hold of the parallel treatment of meteorites.

The principal question involved in the nebular hypothesis seems to be the stability of a rotating mass of gas; but unfortunately this has remained up to now an untouched field of mathematical research. We can only judge of probable results from the investigations which have been made concerning the stability of a rotating mass of liquid. Now it appears that the instability of a rotating mass of liquid first enters through the graver modes of gravitational oscillation. In the case of a rotating spheroid of revolution the gravest mode of oscillation is an elliptic deformation, and its period does not differ much from that of a satellite which revolves round the spheroid so as to graze its surface. Hence, assuming for the moment that a kinetic theory of liquids had been formulated, we should not be justified in applying the hydrodynamical method to this discussion of stability, unless the periodic time of such a satellite were a large multiple of the analogue of the mean free time of a molecule of liquid.

Carrying then this conclusion on to the kinetic theory of meteorites, it seems probable that hydrodynamical treatment must be inapplicable for the discussion of such a theory as the meteoric-nebular hypothesis, unless a similar relation holds good.

These considerations, although of a vague character, will afford a criterion of the applicability of hydrodynamics to the kind of problem suggested by the nebular hypothesis. And certain criteria suggested by this line of thought are found in the paper; they give a measure of the degree of curvature of the average path pursued by a meteorite between two collisions.

After these preliminary investigations, we have to consider what kind of meeting of two meteorites will amount to an "encounter" within the meaning of the kinetic theory.

Is it possible, in fact, that two meteorites can considerably bend their paths under the influence of gravitation, when they pass near one another? This question is considered in the paper, and it is shown that unless the bodies have the dimensions of small planets, the mutual gravitational influence is insensible. Hence, nothing short of absolute impact is to be considered an encounter in the kinetic theory,

and what is called the radius of "the sphere of action" is simply the distance between the centres of a pair when they graze, and is therefore the sum of the radii of a pair, or, if of uniform size, the diameter of one of them.

The next point to consider is the mass and size which must be attributed to the meteorites.

The few samples which have been found on the earth prove that no great error can be committed if the average density of a meteorite be taken as a little less than that of iron, and I accordingly suppose their density to be six times that of water.

Undoubtedly in a meteor-swarm all sizes co-exist (a supposition considered hereafter); for even if originally of uniform size they would, by subsequent fracture, be rendered diverse. But in the first consideration of the problem they have been treated as of uniform size, and as actual sizes are nearly unknown, results are given for meteorites weighing $3\frac{1}{8}$ grams. From these, the values for other masses are easily derivable.

It is known that meteorites are actually of irregular and angular shapes, but certainly no material error can be incurred when we treat them as being spheres.

The object of all these investigations is to apply the formulæ to a concrete example. The mass of the system is therefore taken as equal to that of the sun, and the limit of the swarm at any arbitrary distance from the present sun's centre. The theory is of course more severely tested the wider the dispersion of the swarm, and accordingly in a numerical example the outside limit of the solar swarm is taken at $44\frac{1}{2}$ times the earth's distance from the sun, or further beyond the planet Neptune than Saturn is from the sun. This assumption makes the limit of the isothermal sphere at a distance 16, about half-way between Saturn and Uranus.

In this case the mean velocity of the meteorites in the isothermal sphere is $5\frac{1}{3}$ kilometers per second, being $\sqrt{\frac{6}{5}}$ of the linear velocity of a planet revolving about a central body with a mass equal to 46 per cent. of that of the sun, at distance 16. In the adiabatic layer it diminishes to zero at distance $44\frac{1}{2}$. This velocity is independent of the size of the meteorites. The mean free path between collisions ranges from 42,000 kilometers at the centre, to 1,300,000 kilometers at radius 16, and to infinity at radius $44\frac{1}{2}$. The mean interval between collisions ranges from a tenth of a day at the centre, to three days at radius 16, and to infinity at radius $44\frac{1}{2}$. The criterion of applicability of hydrodynamics ranges from $\frac{1}{60000}$ at the distance of the asteriods to $\frac{1}{3600}$ at radius 16, and to infinity at radius $44\frac{1}{2}$.

All these quantities are ten times as great for meteorites of $3\frac{1}{8}$ kilos., and a hundred times as great for meteorites of $3\frac{1}{8}$ tonnes.

From a consideration of the tables in the paper it appears that,

with meteorites of $3\frac{1}{8}$ kilos., the collisions are sufficiently frequent even beyond the orbit of Neptune to allow the kinetic theory to be applicable in the sense explained. But if the meteorites weigh $3\frac{1}{8}$ tonnes, the criterion ceases to be very small at about distance 24, and if they weigh 3125 tonnes they cease to be very small at about the orbit of Jupiter. It may be concluded then that, as far as frequency of collision is concerned, the hydrodynamical treatment of a swarm of meteorites is justifiable.

Although the numerical results are necessarily affected by the conjectural values of the mass and density of the meteorites, yet it was impossible to arrive at any conclusion whatever as to the validity of the theory without numerical values, and such a discussion as the above was therefore necessary.

I now pass on to consider some results of this view of a swarm of meteorites, and to consider the justifiability of the assumption of an isothermal-adiabatic arrangement of density.

With regard to the uniformity of distribution of kinetic energy in the isothermal sphere, it is important to ask whether or not sufficient time can have elapsed in the history of the system to allow of the equalisation by diffusion.

It is shown therefore in the paper that in the case of the numerical example primitive inequalities of kinetic energy would, in a few thousand years, be sensibly equalised over a distance some ten times as great as our distance from the sun. This result then goes to show that we are justified in assuming an isothermal sphere as the centre of the swarm. As, however, the swarm contracts the rate of diffusion diminishes as the inverse $\frac{5}{2}$ power of its linear dimensions, whilst the rate of generation of inequalities of distribution of kinetic energy, through the imperfect elasticity of the meteorites, increases. Hence, in a late stage of the swarm, inequalities of kinetic energy would be set up, there would be a tendency to the production of convective currents, and thus the whole swarm would probably settle down to the condition of convective equilibrium throughout.

It may be conjectured then that the best hypothesis in the early stages of the swarm is the isothermal-adiabatic arrangement, and later an adiabatic sphere. It has not seemed worth while to discuss this latter hypothesis in detail at present.

The same investigation also gives the coefficient of viscosity of the quasi-gas, and shows that it is so great that the meteor-swarm must, if rotating, revolve nearly without relative motion of its parts, other than the motion of agitation. But as the viscosity diminishes when the swarm contracts, this would probably not be true in the later stages of its history, and the central portion would probably rotate more rapidly than the outside. It forms, however, no part of the scope of this paper to consider the rotation of the system.

The rate of loss of kinetic energy through imperfect elasticity is next considered, and it appears that the rate, estimated per unit time and volume, must vary directly as the square of the quasi-pressure, and inversely as the mean velocity of agitation. Since the kinetic energy lost is taken up in volatilising solid matter, it follows that the heat generated must follow the same law. The mean temperature of the gases generated in any part of the swarm depends on a great variety of circumstances, but it seems probable that its variation would be according to some law of the same kind. Thus, if the spectroscope enables us to form an idea of the temperature in various parts of a nebula, we shall at the same time obtain some idea of the distribution of density.

It has been assumed that the outer portion of the swarm is in convective equilibrium, and therefore there is a definite limit beyond which it cannot extend. Now a medium can only be said to be in convective equilibrium when it obeys the laws of gases, and the applicability of those laws depends on the frequency of collisions. But at the boundary of the adiabatic layer the velocity of agitation vanishes, and collisions become infinitely rare. These two propositions are mutually destructive of one another, and it is impossible to push the conception of convective equilibrium to its logical conclusion. There must, in fact, be some degree of rarity of density and of collisions at which the statistical treatment of the medium breaks down.

I have sought to obtain some representation of the state of things by supposing that collisions never occur beyond a certain distance from the centre of the swarm.

Then from every point of the surface of the sphere, which limits the region of collisions, a fountain of meteorites is shot out, in all azimuths and at all inclinations to the vertical, and with velocities grouped about a mean according to the law of error. These meteorites ascend to various heights, without collision, and, in falling back on to the limiting sphere, cannonade its surface, so as to counterbalance the hydrostatic pressure at the limiting sphere.

The distribution in space of the meteorites thus shot out is investigated in the paper, and it is found that near the limiting sphere the decrease in density is somewhat more rapid than the decrease corresponding to convective equilibrium.

But at more remote distances the decrease is less rapid, and the density ultimately tends to vary inversely as the square of the distance from the centre.

It is clear that according to this hypothesis the mass of the system is infinite in a mathematical sense; for the existence of meteorites with nearly parabolic and hyperbolic orbits necessitates an infinite number, if the loss of the system shall be made good by the supply.

But if we consider the subject from a physical point of view, this conclusion appears unobjectionable.* The ejection of molecules with exceptionally high velocities from the surface of a liquid is called evaporation, and the absorption of others is called condensation. The general history of a swarm, as sketched at the beginning, may then be put in different words, for we may say that at first a swarm gains by condensation, that condensation and evaporation balance, and finally that evaporation gains the day.

If the hypothesis of convective equilibrium be pushed to its logical conclusion, we reach a definite limit to the swarm, whereas if collisions be entirely annulled the density goes on decreasing inversely as the square of the distance. The truth must clearly lie between these two hypotheses. It is thus certain that even the small amount of evaporation, shown by the formulæ derived from the hypothesis of no collision, must be in excess of the truth; and it may be that there are enough waifs and strays in space ejected from other systems to make good loss. Whether or not the compensation is perfect, a swarm of meteorites would pursue its evolution without being sensibly affected by a slow evaporation.

Up to this point the meteorites have been considered as of uniform size, but it will be well to examine the more truthful hypothesis that they are of all sizes, grouped about a mean according to a law of error.

It appears, from the investigation in the paper, that the larger stones move slower, the smaller ones faster, and the law is that the mean kinetic energy is the same for all sizes. It is proved that the mean path between collisions is shorter in the proportion of 7 to 11, and the mean frequency of collision greater in the proportion of 4 to 3, than if the meteorites were of uniform mass equal to the mean. Hence the numerical results found for meteorites of uniform size are applicable to non-uniform meteorites of a mean mass about a quarter greater than the uniform mass; for example, the results for uniform meteorites of $3\frac{1}{8}$ tonnes apply to non-uniform ones of mean mass a little over 4 tonnes.

The means here spoken of refer to all sizes grouped together, but there is a separate mean free path and mean frequency appropriate to each size. These are investigated in the paper, and their values illustrated in a figure. It appears that collisions become infinitely frequent for the infinitely small ones, because of their infinite velocity, and again infinitely frequent for the infinitely large ones, because of their infinite size. There is a minimum frequency of collision for a

* [It must be borne in mind that the very high velocities which occur occasionally in a medium with perfectly elastic molecules, must happen with great rarity amongst meteorites. An impact of such violence that it *ought* to generate a hyperbolic velocity will probably merely cause fracture.—Added November 23, 1888.]

certain size, a little less in radius than the mean radius, and considerably less in mass than the mean mass.

For infinitely small meteorites the mean free path reaches a finite limit, equal to about four times the grand mean free path; and for infinitely large ones, the mean free path becomes infinitely short. It must be borne in mind that there are infinitely few of the infinitely large and infinitely small meteorites. Variety of size does not then, so far, materially affect the results.

But a difference arises when we come to consider the different parts of the swarm. The larger meteorites, moving with smaller velocities, form a quasi-gas of less elasticity than do the smaller ones. Hence the larger meteorites are more condensed towards the centre than are the smaller ones, or the large ones have a tendency to fall down, whilst the small ones have a tendency to rise. Accordingly, the various kinds are to some extent sorted according to size.

An investigation is made in the paper of the mean mass of meteorites at various distances from the centre, both inside and outside of the isothermal sphere, and a figure illustrates the law of diminution of mean mass.

It is also clear that the loss of the system through evaporation must fall more heavily on the small meteorites than on the large ones.

After the foregoing summary, it will be well to briefly recapitulate the principal physical conclusions which seem to be legitimately deducible from the whole investigation; in this recapitulation qualifications must necessarily be omitted or stated with great brevity.

When two meteorites are in collision, they are virtually highly elastic, although ordinary elasticity must be nearly inoperative.

A swarm of meteorites is analogous with a gas, and the laws governing gases may be applied to the discussion of its mechanical properties. This is true of the swarm, from which the sun was formed, when it extended beyond the orbit of the planet Neptune.

When the swarm was very widely dispersed the arrangement of density and of velocity of agitation of the meteorites was that of an isothermal-adiabatic sphere. Later in its history, when the swarm had contracted, it was probably throughout in convective equilibrium.

The actual mean velocity of the meteorites is determinable in a swarm of given mass, when expanded to a given extent.

The total energy of agitation in an isothermal-adiabatic sphere is half the potential energy lost in the concentration from a condition of infinite dispersion.

The half of the potential energy lost, which does not reappear as kinetic energy of agitation, is expended in volatilising solid matter, and heating the gases produced on the impact of meteorites. The heat so generated is gradually lost by radiation.

The amount of heat generated per unit time and volume varies as

the square of the quasi-hydrostatic pressure, and inversely as the mean velocity of agitation. The temperature of the gases volatilised probably varies by some law of the same nature.

The path of a meteorite is approximately straight, except when abruptly deflected by a collision with another. This ceases to be true at the outskirts of the swarm, where the collisions have become rare. The meteorites here describe orbits under gravity which are approximately elliptic, parabolic, and hyperbolic.

In this fringe to the swarm the distribution of density ceases to be that of a gas under gravity; and as we recede from the centre the density at first decreases more rapidly, and afterwards less rapidly than if the medium were a gas.

Throughout all the stages of its history there is a sort of evaporation by which the swarm very slowly loses in mass, but this loss is more or less counterbalanced by condensation. In the early stages the gain by condensation outbalances the loss by evaporation, they then equilibrate, and finally the evaporation may be greater than condensation.

Throughout the swarm the meteorites are to some extent sorted according to size; as we recede from the centre the number of small ones preponderates more and more, and thus the mean mass continually diminishes with increasing distance. The loss by evaporation falls principally on the small meteorites.

A meteor swarm is subject to gaseous viscosity, which is greater the more widely diffused is the swarm. In consequence of this a widely extended swarm, if in rotation, will revolve like a rigid body without relative motion (other than agitation) of its parts.

Later in the history the viscosity will probably not suffice to secure uniformity of rotation, and the central portion will revolve more rapidly than the outside.

[The kinetic theory of meteorites may be held to present a fair approximation to the truth in the earlier stages of the evolution of the system. But later the majority of the meteors must have been absorbed by the central sun and its attendant planets, and amongst the meteors which remain free the relative motion of agitation must have been largely diminished. These free meteorites—the dust and refuse of the system—probably move in clouds, but with so little remaining motion of agitation that (except perhaps near the perihelion of very eccentric orbits) it would scarcely be permissible to treat the cloud as in any respect possessing the mechanical properties of a gas.]*

The value of this whole investigation will appear very different to different minds. To some it will stand condemned as altogether too speculative, others may think that it is better to risk error in the

* Added November 23, 1888.

chance of winning truth. To me at least it appears that the line of thought flows in a true channel, that it may help to give a meaning to the observations of the spectroscopist, and that many interesting problems, here barely alluded to, may perhaps be solved with sufficient completeness to throw light on the evolution of nebulæ and planetary systems.

III. "On the Secretion of Saliva, chiefly on the Secretion of Salts in it." By J. N. LANGLEY, M.A., F.R.S., Fellow of Trinity College, and H. M. FLETCHER, B.A., Trinity College, Cambridge. Received August 17, 1888.

(Abstract.)

Heidenhain has shown that when saliva is obtained by stimulating the chorda tympani, the percentage of salts in the saliva depends upon the rate of secretion, so that the faster the secretion the higher the percentage of salts is up to a limit of about 0·6 per cent. Werther has come to the same conclusion, but finds that the percentage of salts may be as much as 0·77. Both in Heidenhain's and in Werther's experiments there are many exceptions to this rule, attributed by them to variations in the rate of secretion of saliva during the time of collecting any one sample.

We have repeated, with some modifications, the experiments of Heidenhain, paying especial attention to the rate of secretion of saliva, and find in 10 out of 11 cases, that his law of an increase in the percentage of salts with an increase in the rate of secretion holds. The single exception may be due to a modification of the blood-flow through the gland during the time of collecting the saliva. The slowly secreted saliva contains a low percentage of salts, whether it is produced by a weak nerve stimulus, or by a very strong nerve stimulus which lowers the irritability of the nerve-fibres.

We do not find any rate of secretion, beyond which an increase in rate fails to increase the percentage of salts in the saliva. The increment in the percentage of salts decreases, however, with each equal successive increment in the rate of secretion.

As a rule in saliva obtained by injecting pilocarpin, the percentage of salts follows Heidenhain's law; we take the exceptions to be due to the action of pilocarpin upon the circulation, the blood-flow through the gland being less than normally accompanies the degree of stimulation of the gland cells.

The percentage of salts in saliva obtained by stimulating the sympathetic is higher than corresponds to its rate of secretion, the saliva obtained by stimulating the chorda being taken as a basis of comparison; this sympathetic saliva may be secreted at $\frac{1}{180}$th of the rate